DEPARTMENT OF COMMERCE

# TECHNOLOGIC PAPERS
OF THE
# BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

## No. 130

# A COMPARISON OF THE HEAT INSULATING PROPERTIES OF SOME OF THE MATERIALS USED IN FIRE-RESISTIVE CONSTRUCTION

BY

WALTER A. HULL, Associate Physicist
*Bureau of Standards*

ISSUED NOVEMBER 12, 1919

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# A COMPARISON OF THE HEAT INSULATING PROPERTIES OF SOME OF THE MATERIALS USED IN FIRE-RESISTIVE CONSTRUCTION

By Walter A. Hull

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## I. INTRODUCTION

This investigation was preliminary to the investigation of the fire-resistive properties of full-size building columns, and was made for the purpose of determining the heat-insulating properties of the materials commonly used as protective coverings for steel. Under many conditions, particularly in the case of industrial furnaces, steam-pipe coverings, etc., the insulating value of a material depends almost wholly on its thermal conductivity. In the case of a column or other structural unit exposed to an accidental fire, a different problem is presented, involving several important factors in addition to that of thermal conductivity. An accidental fire starts with all the materials at ordinary temperatures, somewhere in the neighborhood of 20° C (68° F). Atmospheric and surface temperatures increase, in the case of severe fires, to as high as 1000° C (1832° F) or even higher. The rise in temperature may be fast or slow, but in either case the fire is over and the temperatures drop back to normal, or nearly so, in the course of a few hours. The function of a protective covering is to prevent heat from reaching the load bearing portion of the column, or other unit, in sufficient amount to raise its temperature so as to seriously weaken it, either permanently or temporarily. In a temporary exposure of this sort, the insulating efficiency of the covering material depends chiefly upon two properties, namely, its resistance to heat flow, which is the reciprocal of its thermal conductivity, and its ability to absorb or its tendency to generate heat. Heat may be absorbed in three principal ways:

1. As sensible heat, taken up by the material in the course of its rise in temperature.
2. As latent heat, taken up by the evaporation of water.
3. As the heat of dissociation, taken up by endothermic chemical reaction, as in the decarbonation of limestone and the dehydration of gypsum.

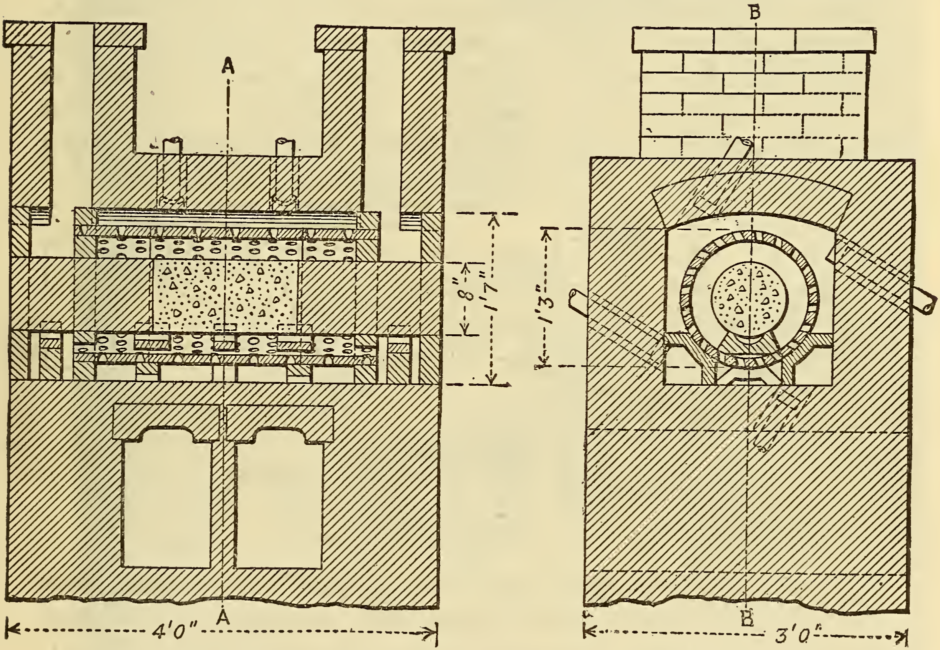
On the other hand, heat may be released within the material itself in one or more ways, but principally by the oxidation, or even combustion, of its organic constituents.

Mathematical calculations necessary for the comparison of the insulating properties of materials in which the above factors have to be considered, would be exceedingly complex even if the thermal effects of these and other progressive changes in the materials were known quantitatively. In view of these considerations, it was regarded as essential that comparisons be made by experimental methods rather than by calculations involving the many factors to be taken into account. The most promising method, as well as the simplest, seemed to be that of subjecting specimens, identical in form and size, of the various materials to the same heat treatment, and measuring temperatures at definite points within the specimens while the tests were in progress. It was believed that considerable information regarding the characteristic insulating properties of various materials would be derived from a comparison of the time-temperature curves obtained in this way. It was thought, also, that in the case of concrete and gypsum, information would be gained bearing on the extent of deterioration in load-bearing members made up either partially or wholly of these materials.

For this purpose all of the materials to be tested were made up into specimens in the form of solid cylinders, 8 inches in diameter by 16 inches long, each provided with four holes, ¼ inch in diameter, extending through the piece longitudinally, for the insertion of thermocouples. These holes were not located in one plane, but were staggered to such an extent that the outer ones would not effect heat flow toward the regions occupied by the inner ones.

## II. FURNACE USED IN THE INVESTIGATION

The gas-fired furnace built for the purpose of making the heat exposures is shown in Figs. 1 and 2. The furnace was long enough to take three 16-inch cylinders, placed end to end in a horizontal position. The test specimen was placed in the middle, with a similar cylinder made of a material of moderately low thermal conductivity, such as cinder concrete or fire clay, at each end. The end cylinders served to minimize end flow of heat and to provide support and mechanical protection for the thermocouples. The three cylinders were placed with their ends in contact and the joints were covered with asbestos cement.



Section B-B.

Section A-A.

Fig. 1.—*Furnace for testing specimens*

In order to avoid the difficulties which would attend the placing of thermocouples and the covering of joints after the cylinders were placed in the furnace, a special device was provided on which the cylinders could be set up outside the furnace, and then placed inside as a unit. This device is shown in Fig. 2. It consisted essentially of two parallel pieces of gas pipe, supported and rigidly held at one end by a small roller carriage and at the other by a wooden yoke. This device was supported on a narrow table which had a hinged top, so that after the cylinders were run into the furnace, the table top could be tilted in order to lower the carriage end of the cylinder support simultaneously with the yoke end, which was handled by a man at the other end of the furnace. This made it comparatively easy to place the three cylinders at once without getting them out of alignment.

The furnace was heated by four pairs of gas burners of the blast type. One pair of burners was located in the top of the furnace, one pair in the bottom and a pair in each side. Each pair was placed at such an angle that the line of discharge was approximately tangential to the perforated guard ring shown in Fig. 1. The flames from successive pairs of burners impinged obliquely on the sides, top, and bottom of the furnace, flowing annularly in the space surrounding the guard ring. The burners were so placed that all discharged in the same direction in respect to the guard ring, and the flames from successive burners followed each other around until their force was spent, after which the heated gases were drawn through the perforations in the guard ring by a feeble stack draft and passed quietly out through vents at the ends of the furnace. The holes in the guard ring were located at such an angle that the tendency of the moving gases was to glide past them rather than to catch on their edges and be driven forcibly through toward the specimen. This arrangement of burners and guard ring was designed to prevent the local inequalities in the heat distribution which would result if the flames from the burners were permitted to impinge against the specimen, even if first deflected by baffles. The guard ring served the further purpose of screening the specimen from the effect of an exchange of radiation with unequally heated surroundings, such as hotter and colder spots in the furnace lining. Nearly all the radiant energy received by the

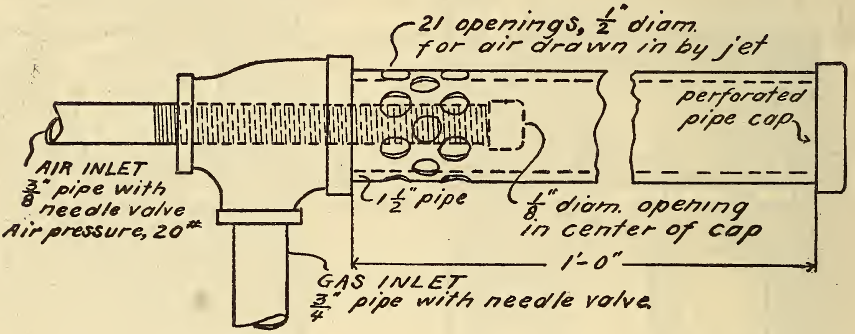


Fig. 3.—*Type of gas burner used*

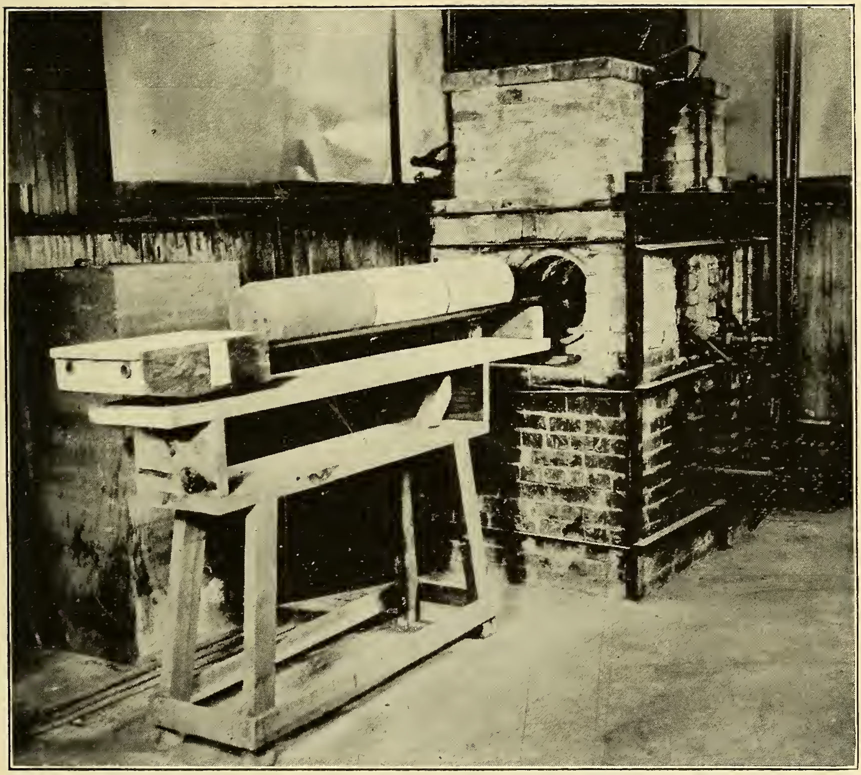


FIG. 2.—*Furnace and device for placing specimens in furnace*

specimen came from the guard ring which was itself quite uniformly heated. This design made it possible to obtain fairly satisfactory heat distribution in a furnace that was compact and easily heated.

The type of gas burner used is shown in Fig. 3. The burners were made in the shop of the Bureau. Air under a pressure of 15 to 20 pounds, entering through the inner, 3/8-inch pipe, passed through a hole in the cap about 1/8 inch in diameter, forming a jet which created a partial vacuum, sucking in more air through the openings in the 1½-inch outer pipe, or barrel, of the burner, and causing rapid mixing with gas, which entered through the ¾-inch pipe shown. Inasmuch as the burners had to be operated at low capacity at the beginning and again near the end of the burn, perforated caps were used on the ends of the barrels to prevent back firing. These burners were capable of giving good combustion at both low and high capacity, which was essential to the sort of furnace control called for in this work.

## III. TEMPERATURE MEASUREMENTS

Temperatures within the specimen were measured by means of thermocouples at points ½, 1½, 2½, and 3½ inches, respectively, from the cylindrical surface of the specimen midway between the ends. Furnace temperatures were measured at one point above and one point below the middle of the specimen, between the specimen and the guard ring.

Platinum-platinum-rhodium thermocouples were used and in most of the work the couples extended through the length of all three cylinders, the positive ends extending out at one end and the negative at the other. Cold junctions were kept in ice baths.

The thermocouples were protected from contamination by covering that portion which was within the specimen with a quartz tube of small diameter. The holes in the end cylinders were enlarged somewhat, at the end next to the specimen, so that the quartz tube could extend a short distance beyond each end of the specimen without serious danger of being broken by a slight rotation of any cylinder, in placing the cylinders or removing them. It was not necessary to protect the thermocouple wires through the end cylinders because the danger of contamination in the fire-clay cylinders or in clinker-concrete cylinders that had already been through a test was not great.

Temperature records were made by a Hartman and Braun six-point recording galvanometer. The thermocouples differed somewhat from each other in their temperature emf relations.

They were calibrated in conjunction with the recorder by comparing with a standard couple, of known calibration, in the following manner. A given couple was placed in a suitable electrically heated tube furnace, together with the standard couple, both being so placed that their junctions would be at the same temperature. When the furnace had been brought to a given temperature, this temperature was held nearly constant, and at a given time the indication of the standard couple was read on a calibrated potentiometer indicator. At the same moment a switch was opened in the circuit connecting the couple which was being calibrated, and the recorder indicated by a break in the record the time at which the reading of the potentiometer, in circuit with the standard couple, had been made. This made it possible for one operator to make a satisfactory calibration of the thermocouple recorder combination. These calibrations were repeated in the course of the work and the equipment was found to have maintained the original temperature-deflection relations. It was of course necessary to convert the recorder records into corrected temperature records, using the calibration of the recorder with each individual couple as a basis for the conversion. In order to expedite this part of the work, and at the same time to secure more accurate readings than could otherwise be done by ordinary methods of reading from the coarsely ruled recorder charts, the following device was adopted. For each individual calibration a curve was plotted, using temperatures as ordinates and recorder deflections as abscissas. Each of these curve sheets was mounted on card board and a portion cut away, leaving the edge of the paper identical with the temperature-deflection curve. A reference line on the mounting corresponded to the zero line of the recorder. A suitable board was provided, with a guide along the left-hand edge and a reference line on the board, this reference line being so located as to coincide with the reference line on the mounting previously referred to. To use this conversion curve, the recorder chart was placed on the board with its zero line over the reference line and fastened in place with thumb tacks. The mounted curve was then placed over the recorder chart and against the guide. To interpret the successive punch marks on the chart, the conversion curve was moved along, vertically, until the curve covered one of the dots, while the corresponding position on the vertical scale of the curve sheet gave the correct temperature. This device was found to be a satisfactory time saver, as corrected readings including corrections for both the recorder and the thermocouple could be obtained quickly in one operation.

## IV. TIME-TEMPERATURE CURVE FOLLOWED IN TESTS

It was the purpose to subject all specimens to the same heat exposure so as to obtain comparable records from all materials. It was decided to use a rather slow temperature rise in order that none of the specimens should spall or break up to such an extent as to materially affect the heat flow, and so render comparisons of insulating properties impossible. The furnace temperatures were accordingly raised at a nearly uniform rate to approximately 927° C (1700° F) in 1 hour and 30 minutes, and this temperature was then held as nearly constant as possible for 2 hours, giving an exposure of 3 hours and 30 minutes, at an average furnace temperature of approximately 700° C (1,292° F).

## V. MATERIALS TESTED

The materials included in the investigation were as follows:

1. Clays that are used in the manufacture of hollow-tile fireproofing.
2. Concretes, including two proportions, with each of a number of aggregates.
3. Gypsum specimens supplied by three manufacturers. The variables included kind of plaster, kind of filler, and percentage of water.
4. One specimen of lime mortar.
5. One specimen of a patented material called "Radix."

Burned clay specimens were made from each of the following raw materials:

1. Specimens Nos. 1122, 1126, and 1128 were from clay from the works of the National Fireproofing Co., at Perth Amboy, N. J. This material may be classed as an impure fire clay. This clay, as well as the others used in the investigation, is used for the manufacture of hollow-tile fireproofing, as stated above.
2. Specimens 1136 and 1138 were from clay from the Waynesburg, Ohio, plant of the Whitacre Fireproofing Co. This material is a plastic, coal-measure fire clay, commonly known as a No. 2 fire clay. The material supplied was ground at the factory, ready for tempering.
3. Specimens Nos. 1141, 1142, and 1143 were from clay from the Chicago plant of the Whitacre Fireproofing Co. This is a plastic surface clay.

## VI. MAKING AND BURNING OF CLAY SPECIMENS

The clay cylinders were made and burned in the laboratories of the Bureau of Standards, at Pittsburgh, and the equipment of the Clay Products Section was used for tempering, drying, and burning. The clay was tempered to the consistency commonly referred to as stiff mud and molded by ramming in wooden molds. Holes for thermocouples were provided for by means of suitably placed rods, of ¼-inch steel. After the mold was filled the rods were withdrawn. After molding, the cylinders were carefully dried and then burned. These specimens were much thicker than the walls of the ware commonly made from these materials and a long time was found to be required for proper oxidation in burning. Although the necessary time was given and care was taken in the entire burning process, all of the specimens were cracked, to some extent, in the burning. The Chicago clay, being of a nature which will not stand burning to as high temperature as the others, was given a light burn, perhaps too light to make the comparison of the insulating properties of the three clays strictly fair, inasmuch as it may be that the greater porosity of the specimens from the Chicago clay was due in part to the lighter burning. The Perth Amboy and the Waynesburg clays were burned together and both were given what was considered a fairly hard burn. The difference in porosity in the burned specimens from these two clays is attributable to the nature of the clays. The differences seen in the diameters of the different burned clay specimens are due to differences in shrinkage, as all specimens were made in the same mold.

## VII. KINDS OF CONCRETE INCLUDED

As shown in Table 1, the list of concretes includes 1 : 2 : 4 and 1 : 3 : 6 mixtures with gravel, cinders of several grades, limestone, trap rock, and blast furnace slag as aggregates. One set of specimens was made with cement and cinders, without sand; and another set was made from 1 : 3 : 6 gravel concrete, in which 15 per cent of the cement by weight was replaced by hydrated lime.

### TABLE 1.—Summarized Data for Burned Clay and Concrete Specimens

BURNED CLAY SPECIMENS

| Specimen No. | Source of raw material | Porosity in burned specimens | Diameter of cylinder | Weight of specimen | Average furnace temperature during test | Time at which 600° C was reached | | Temperatures in specimens at end of 3 hours 30 minutes | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | At depth of 1½ inches | At depth of 2½ inches | At depth of 1½ inches | At depth of 2½ inches | At depth of 3½ inches |
| | | Per cent | Inches | Pounds | °C | H. m. | H. m. | °C | °C | °C |
| 1122 | Perth Amboy, N. J. | ........ | $7\frac{3}{4}$ | 52.31 | 719 | 1 46 | 2 06 | 880 | 880 | 840 |
| 1126 | .....do | 23.80 | $7\frac{15}{16}$ | 54.90 | 709 | 1 58 | 2 12 | 870 | 870 | 830 |
| 1128 | .....do | 13.90 | $8\frac{1}{16}$ | 53.75 | 717 | 1 54 | 2 12 | 880 | 860 | 820 |
| 1136 | Waynesburg, Ohio | 4.65 | $8\frac{1}{4}$ | 67.50 | 699 | 1 56 | 2 11 | 855 | 850 | 815 |
| 1138 | .....do | ........ | $8\frac{7}{16}$ | 69.90 | 737 | 1 50 | 2 8 | 875 | 870 | 825 |
| 1141 | Chicago, Ill. | 31.40 | $8\frac{1}{4}$ | 52.50 | 714 | 2 12 | 2 41 | 790 | 745 | 685 |
| 1142 | .....do | 36.70 | $8\frac{1}{4}$ | 57.30 | 709 | 2 18 | 2 38 | 785 | 770 | 695 |
| 1143 | .....do | ........ | $8\frac{3}{8}$ | 54.31 | 746 | 2 12 | 2 36 | 810 | 780 | 705 |

## TABLE 1—Continued

CONCRETE SPECIMENS

| Specimen No. | Coarse aggregate | Proportions | Age when tested |  | Weight before test | Loss in weight |  | Average furnace temperature during test | Time at which dehydration lag terminated | Time at which 600° C was reached |  | Temperatures in specimens at end of 3 hours 30 minutes |  |  | Breaking load |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  |  |  | At depth of 1½ inches | At depth of 2½ inches | At depth of 1½ inches | At depth of 2½ inches | At depth of 3½ inches |  |
|  |  |  | Mos. | Days | Pounds | Pounds | Per cent | °C | H. m. | H. m. | H. m. | °C | °C | °C | Pounds |
| 1211 | Pittsburgh gravel | 1:2:4 | 4 | 12 | 65.25 | 5.25 | 8.05 | 750 | 1 06 | 1 58 | 2 34 | 810 | 755 | 720 | .......... |
| 1212 | .....do | 1:2:4 | 4 | 25 | 66.25 | 4.75 | 7.17 | 775 | 1 06 | 1 55 | 2 22 | 840 | 815 | 750 | .......... |
| 1214 | .....do | 1:2:4 | 10 | 27 | 64.62 | 4.00 | 6.20 | 705 | 1 05 | 2 09 | 2 34 | 800 | 790 | 740 | .......... |
| 1221 | .....do | 1:3:6 | 4 | 25 | 65.00 | 4.47 | 6.90 | 790 | 1 00 | 1 50 | 2 26 | 840 | 770 | 745 | .......... |
| 1222 | .....do | 1:3:6 | 5 | 3 | 63.88 | 3.50 | 5.48 | 730 | 1 08 | 2 06 | 2 34 | 830 | 755 | 735 | .......... |
| 1223 | .....do | 1:3:6 | 4 | 3 | 65.50 | 4.25 | 6.50 | 700 | 1 06 | 2 08 | .......... | 810 | .......... | 720 | .......... |
| 1232 | Clinker | 1:2:4 | 3 | 9 | *a*53.62 | .......... | .......... | 732 | 1 28 | 2 08 | 2 38 | 810 | 775 | 730 | .......... |
| 1233 A | .....do | 1:2:4 | 8 | 22 | 54.88 | 3.50 | 6.37 | 696 | 1 20 | 2 20 | 2 44 | 780 | 760 | 690 | 16 130 |
| 1234 | .....do | 1:2:4 | 3 | 11 | 53.37 | 4.88 | 9.15 | 716 | 1 20 | 2 15 | 2 40 | 810 | 775 | 750 | .......... |
| 1241 | .....do | 1:3:6 | 4 | 27 | 54.62 | 4.12 | 6.90 | 715 | 1 22 | 2 20 | 2 39 | 800 | 760 | 720 | .......... |
| 1242 | .....do | 1:3:6 | 5 | 2 | 54.37 | 3.88 | 7.23 | 683 | 1 22 | 2 07 | 2 51 | 820 | 745 | 730 | .......... |
| 1244 | .....do | 1:3:6 | 9 | 11 | 52.12 | 3.00 | 5.76 | 689 | 1 12 | 2 14 | 2 30 | 800 | 790 | 760 | .......... |
| 1251 | Limestone | 1:2:4 | 4 | 23 | 65.94 | 7.44 | 11.18 | 725 | 1 22 | 2 24 | 3 08 | 740 | 660 | 610 | .......... |
| 1254a[b] | .....do | 1:2:4 | 3 | 10 | 66.88 | 8.18 | 12.24 | 703 | 1 26 | 2 30 | 2 58 | 730 | 700 | 620 | .......... |
| 1254b | .....do | 1:2:4 | 3 | 4 | 66.31 | 8.44 | 12.70 | 726 | 1 16 | 2 30 | 2 50 | 730 | 710 | 620 | .......... |
| 1254d | .....do | 1:2:4 | 3 | 13 | 66.50 | 8.75 | 13.18 | 719 | 1 22 | 2 32 | 2 56 | 720 | 700 | 610 | .......... |
| 1255a[c] | .....do | 1:2:4 | 2 | 29 | 65.50 | 6.50 | 9.92 | 708 | 1 22 | 2 25 | 2 52 | 730 | 705 | 620 | 30 650 |
| 1255b | .....do | 1:2:4 | 3 | 2 | 65.00 | 6.00 | 9.23 | 720 | 1 24 | 2 24 | 2 48 | 720 | 710 | 630 | 18 500 |
| 1255d | .....do | 1:2:4 | 3 | 12 | 64.19 | 7.00 | 10.90 | 720 | 1 25 | 2 28 | 2 56 | 730 | 690 | 630 | .......... |
| 1256a[d] | .....do | 1:2:4 | 3 | 2 | 66.20 | 6.75 | 10.20 | 692 | 1 22 | 2 34 | 3 00 | 710 | 680 | 630 | 26 400 |
| 1256d | .....do | 1:2:4 | 3 | 7 | 65.20 | 7.37 | 11.32 | 724 | 1 25 | 2 26 | 2 54 | 730 | 715 | 640 | .......... |
| 1265 | .....do | 1:3:6 |  | 15 | 63.19 | 5.81 | 9.20 | 707 | 1 22 | 2 38 | 2 58 | 700 | 680 | 655 | .......... |
| 1266 | .....do | 1:3:6 | 8 | 13 | 62.50 | 6.12 | 9.78 | 752 | 1 15 | 2 16 | 2 40 | 750 | 720 | 680 | .......... |
| 1268 | .....do | 1:3:6 | 7 | 9 | 63.37 | 6.12 | 9.60 | 723 | 1 12 | 2 16 | 2 40 | 760 | 725 | 660 | .......... |
| 1281[e] | Pittsburgh gravel | 1:3:6 | 5 | 2 | 63.88 | 3.88 | 5.85 | 760 | 1 05 | 2 02 | 2 25 | 810 | 770 | 730 | .......... |
| 1282 | .....do | 1:3:6 | 5 | 4 | 63.62 | 4.25 | 6.68 | 730 | 1 10 | 2 08 | 2 38 | 820 | 755 | 715 | .......... |
| 1283 | .....do | 1:3:6 | 9 | 26 | 62.75 | 3.37 | 5.37 | 700 | 1 08 | 2 02 | 2 31 | 820 | 760 | 710 | .......... |
| 1291 | Soft coal cinders | 1:3:6 | 4 | 5 | 47.50 | 2.75 | 5.78 | 691 | 1 10 | 2 10 | 2 32 | 830 | 800 | 760 | .......... |
| 1292 | .....do | 1:3:6 | 4 | 6 | 46.50 | 2.81 | 6.05 | 717 | 1 06 | 1 58 | 2 24 | 860 | 810 | 760 | .......... |
| 1291a | .....do | 1:0:6 | 4 | 0 | 34.50 | 3.75 | 10.88 | 720 | 0 52 | 1 52 | 2 12 | 920 | 870 | 835 | .......... |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1311 | Trap rock | 1:2:4 | 5 | 3 | 69.12 | 3.62 | 5.24 | 721 | 1 20 | 2 16 | 2 36 | 785 | 770 | 690 | .......... |
| 1312 | .....do | 1:2:4 | 5 | 6 | 68.19 | 3.81 | 5.59 | 716 | 1 25 | 2 22 | 2 32 | 780 | 780 | 700 | .......... |
| 1313 | .....do | 1:2:4 | 7 | 25 | 68.88 | 3.62 | 5.25 | 722 | 1 18 | 2 20 | 2 44 | 785 | 755 | 710 | .......... |
| 1321 | .....do | 1:3:6 | 8 | 21 | 67.00 | 3.75 | 5.60 | 731 | 1 18 | 1 58 | 2 32 | 825 | 790 | 715 | .......... |
| 1323 | .....do | 1:3:6 | 7 | 27 | 67.31 | 3.62 | 5.28 | 705 | 1 18 | 2 12 | 2 42 | 785 | 760 | 690 | 8 500 |
| 1331 | Blast furnace slag | 1:2:4 | 4 | 22 | 59.31 | 4.56 | 7.68 | 742 | 1 24 | 2 10 | 2 44 | 815 | 770 | 700 | .......... |
| 1332 | .....do | 1:2:4 | 4 | 27 | 59.00 | 4.50 | 7.62 | 738 | 1 30 | 2 24 | 2 55 | 780 | 740 | 700 | .......... |
| 1333 | .....do | 1:2:4 | 8 | 26 | 59.12 | 4.25 | 7.20 | 699 | 1 38 | 2 24 | 2 51 | 775 | 740 | 660 | 16 420 |
| 1341 | .....do | 1:3:6 | 3 | 19 | 57.25 | 3.31 | 5.78 | 724 | 1 30 | 2 28 | 2 52 | 770 | 730 | 660 | .......... |
| 1342 | .....do | 1:3:6 | 3 | 20 | 57.12 | 3.25 | 5.69 | 718 | 1 40 | 2 18 | 2 44 | 795 | 760 | 660 | .......... |
| 1343 | .....do | 1:3:6 | 4 | 2 | 56.25 | 3.12 | 5.55 | 749 | 1 30 | 2 03 | 2 26 | 830 | 800 | 670 | .......... |

[a] Specimen burned twice. Total loss in weight 5.37 pounds.

[b] 1254a, 1254b, and 1254d stored in damp closet.

[c] 1255a, 1255b, and 1255d stored in work room.

[d] 1256a, 1256b, and 1256d stored in dry-air cans.

[e] 1281, 1282, and 1283 had 15 per cent of the cement replaced by lime hydrate.

TABLE 2.—Summarized Data for Gypsum Specimens

| Specimen No. | Source of raw material | Mixture | | Approximate age | Weight before test | Loss in weight | | Average furnace temperature during test | Time at which dehydration lag ended | Time at which 600°C was reached | | Temperatures in specimen at end of 3 hours 30 minutes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Plaster | Water | | | | | | | At depth of 1½ inches | At depth of 2½ inches | At depth of 1½ inches | At depth of 2½ inches | At depth of 3½ inches |
| | | | | Mos. | Pounds | Pounds | Per cent | °C | H. m. | H. m. | H. m. | °C | °C | °C |
| 1412 a | Middle West | 60 | 40 | 5 | 31.62 | 7.18 | 22.62 | 723 | 2 35 | (b) | (b) | 530 | 215 | 135 |
| 1413 a | do | 60 | 40 | 5 | 31.75 | 7.31 | 23.10 | 697 | 2 30 | (b) | (b) | 475 | 190 | 120 |
| 1421 c | do | 60 | 40 | 5 | 33.12 | 6.69 | 20.20 | 718 | 3 15 | (b) | (b) | 480 | 180 | 115 |
| 1422 c | | 60 | 40 | 5 | 32.88 | 6.62 | 20.07 | 727 | 3 15 | (b) | (b) | 465 | ........ | 120 |
| 1423 c | | 60 | 40 | 5 | 32.88 | 6.69 | 20.35 | 714 | 2 40 | (b) | (b) | 430 | 175 | 120 |
| 1431 d | Middle West | 58 | 42 | 6 | 29.25 | 6.81 | 23.25 | 729 | 2 30 | (b) | (b) | 505 | 195 | 120 |
| 1432 d | do | 58 | 42 | 6 | 29.25 | 6.69 | 22.85 | 732 | 3 00 | 3 50 | (b) | 560 | 240 | 115 |
| 1433 d | do | 58 | 42 | 7 | 30.25 | 6.75 | 22.30 | 705 | 2 40 | (b) | (b) | 520 | 230 | 120 |
| 1441 e | Nova Scotia | 60 | 40 | 4 | 31.88 | 6.44 | 20.20 | 755 | 3 20 | (b) | (b) | 440 | 135 | 120 |
| 1442 e | do | 60 | 40 | 6 | 31.62 | 6.12 | 19.32 | 710 | 2 30 | (b) | (b) | 370 | 160 | 125 |
| 1443 e | | 60 | 40 | 5 | 31.62 | 6.37 | 20.13 | 737 | 2 30 | (b) | (b) | 410 | 160 | 120 |
| 1451 e | Nova Scotia | 50 | 50 | 5 | 24.25 | 5.06 | 20.90 | 748 | 3 20 | (b) | (b) | 480 | 140 | 115 |
| 1452 e | do | 50 | 50 | 5 | 24.37 | 4.75 | 19.50 | 704 | 2 40 | (b) | (b) | 460 | 170 | 120 |
| 1453 e | do | 50 | 50 | 6 | 24.12 | 4.75 | 19.70 | 702 | 3 10 | (b) | (b) | 440 | 180 | 120 |
| 1462 e | do | 45 | 55 | 5 | 20.88 | 4.12 | 19.72 | 726 | 2 50 | 3 28 | (b) | 605 | 225 | 130 |
| 1463 e | do | 45 | 55 | 5 | 20.88 | 4.00 | 19.18 | 740 | 3 00 | (b) | (b) | 485 | 170 | 130 |
| 1471 e | do | 40 | 60 | 5 | 17.75 | 5.62 | 31.60 | 732 | 1 45 | (b) | (b) | 530 | 240 | 135 |
| 1472 e | do | 40 | 60 | 5 | 17.62 | 4.37 | 24.77 | 725 | 2 40 | 4 00 | (b) | 530 | 310 | 125 |
| 1473 e | do | 40 | 60 | 6 | 17.62 | 3.37 | 19.90 | 697 | 2 40 | (b) | (b) | 505 | 205 | 130 |
| 1481 f | Middle West | 50 | 50 | 6 | 24.62 | 5.00 | 20.35 | 721 | 2 30 | (b) | (b) | 510 | 170 | 120 |
| 1482 f | do | 50 | 50 | 6 | 23.88 | 4.75 | 19.90 | 721 | 2 40 | (b) | (b) | 515 | 180 | 120 |
| 1484 f | do | 50 | 50 | 6 | 24.50 | 4.88 | 19.90 | 702 | 2 40 | (b) | (b) | 500 | 180 | 120 |
| 1491 f | do | 55 | 45 | 6 | 26.12 | 4.50 | 17.27 | 712 | 2 40 | (b) | (b) | 530 | 240 | 140 |
| 1492 f | do | 55 | 45 | 6 | 26.12 | ........ | ........ | 713 | 2 40 | (b) | (b) | 550 | 210 | 125 |
| 1493 f | do | 55 | 45 | 6 | 26.12 | 4.50 | 17.27 | 715 | 2 50 | (b) | (b) | 555 | 270 | 125 |
| 1501 f | do | 60 | 40 | 6 | 30.88 | 6.12 | 19.80 | 699 | 3 30 | (b) | (b) | 410 | 145 | 105 |
| 1502 f | do | 60 | 40 | 6 | 31.75 | ........ | ........ | 704 | 2 45 | (b) | (b) | 400 | 155 | 120 |
| 1503 f | do | 60 | 40 | 6 | 31.25 | 6.37 | 20.38 | 704 | 3 05 | (b) | (b) | 450 | 150 | 115 |
| 1491 | Second burn g | ........ | ........ | ........ | ........ | ........ | ........ | 725 | (h) | 2 05 | 2 43 | 790 | 730 | 700 |
| 1502 | do. g | ........ | ........ | ........ | ........ | ........ | ........ | 710 | (h) | 2 34 | 2 58 | 750 | 690 | 635 |
| (i) | | ........ | ........ | 10 | 52.37 | 6.88 | ........ | 688 | 1 40 | 2 30 | 3 24 | 730 | 615 | 505 |
| (j) | | ........ | ........ | 4 | 31.56 | 17.44 | ........ | 720 | ........ | (b) | (b) | 280 | 195 | 150 |

[a] Second settle stucco; filler of cut excelsior.
[b] Not reached.
[c] Second settle stucco; filler of asbestos fiber.
[d] First settle stucco; filler of cut excelsior.
[e] No filler used.
[f] Small quantity wood chip filler.
[g] See data above for first burn.
[h] No lag.
[i] Lime mortar 1:4.
[j] New insulating material called "Radix."

Universal Portland Cement and Pittsburgh river sand of a grade commonly used in concrete were used throughout the series.

The gravel was the Pittsburgh washed river gravel commonly used in the Pittsburgh district for concrete. This gravel is fairly well graded. It is rather coarse for reinforced concrete, although it is quite generally used for such work. For this investigation the dried gravel was passed over a ½-inch screen to remove a variable quantity of fine material.

The Pittsburgh gravel is made up of pebbles which obviously vary considerably from each other in both form and composition. Among them is found a fair proportion of rather thin oval ones that are seen to be sandstone pebbles. Some of these are moderately soft and weak. There is also a considerable proportion of more nearly round, harder pebbles, varying in color, and presumably in composition, but undoubtedly high in quartzose consituents. Scattered among the pebbles included in these two classes, there are a few rounded, rather small ones, light in color and rather coarsely crystalline, which are composed of vein quartz, and an occasional specimen of a dark-colored variety, the individual pebbles of which are rather small, rounded, and composed of cherty material. Like most gravels, this material is of a composition which is favorable to destructive expansion when exposed to severe heat. It may be said, however, that the supply of gravel used in this investigation contained a higher proportion of the sandstone pebbles and less of those of nearly pure quartz than some of the gravel used in the Pittsburgh district.

Cinders were obtained from boilers using bituminous coal from the Pittsburgh seam. The clinkers for specimens Nos. 1232 to 1244 were prepared from the boiler refuse by screening out the fines through a ½-inch screen and picking out the larger pieces of coke by hand. The large pieces of fused cinder were broken up and included, together with additional fused material that was picked out from the general pile and crushed. This produced an aggregate that was practically free from ashes, low in combustible material, and high in fused cinders. It represents something of considerably better grade than would ordinarily be secured commercially from bituminous coal furnace refuse.

Cinders for specimens Nos. 1291 and 1292 were obtained from the same sort of boiler refuse as that just referred to, but were prepared by passing over a ½-inch screen to remove the fines and then breaking up the large pieces to sizes that would pass a 1½-

inch screen. This aggregate contained a large proportion of combustible material, largely in the form of soft coke.

The aggregate for No. 1291a was unscreened, pile-run material, with the large pieces reduced to pass through a 1½-inch screen.

The limestone aggregate was obtained from quarries at West Winfield, Pa. It was a fairly well graded aggregate, practically all of which would pass a 1-inch screen. The West Winfield material is high calcium limestone.

The trap rock was of a grade used for concrete in the New York City district. That supplied for this work was rather coarse and not well graded.

The slag aggregate was of a grade obtained from piles or banks of blast-furnace slag in the Pittsburgh district. The bank slag had been crushed and sized and was well graded.

The lime hydrate used in the concrete for specimens 1281 to 1283 was a composite of several brands of hydrate, all of which would pass the specifications of the National Lime Manufacturers' Association.

The lime-mortar specimen was made from a mixture of Speed brand lime hydrate, which is a high calcium hydrate, with Pittsburgh sand, in the proportion of 1:4, by weight.

The concrete specimens were made up in the laboratory of the Cement Section of the Bureau of Standards, at Pittsburgh, by men experienced in such work. Mixing was done by hand. Approximately the same consistency was maintained throughout the series. The concrete was made soft enough for good working qualities and was of about the consistency secured, with dry materials, by the addition of 8 per cent of water in the making of 1 : 2 : 4 and 1:3:6 gravel concretes. The specimens were made in iron molds in which ¼-inch rods were suitably placed to provide the holes for the thermocouples. The rods were withdrawn before the specimens were removed from the molds. The cylinders were left in the molds for 24 hours and then stored for 6 days in a damp closet, after which they were kept in a steam-heated work room, at ordinary temperatures. This does not apply to the specimens in that part of the series from No. 1254a to No. 1256d, inclusive, which were given different seasoning conditions for the purpose of investigating the effect of these conditions on the thermal properties of the concrete.

Specimens No. 1254a to No. 1254d were kept in the molds for 24 hours and then in a damp closet for the remainder of a seasoning period of approximately 3 months.

Specimens No. 1255a to No. 1255d were kept in the molds for 24 hours, in the damp closet for 6 days, and in a work room, at ordinary temperatures, for the remainder of approximately 3 months.

Specimens No. 1256a to No. 1256d were kept in the molds for 24 hours, in the damp closet for 6 days, and for the remainder of approximately 3 months in oil-sealed cans in which the humidity was kept low by means of sulphuric acid contained in beakers.

All the gypsum specimens were made by manufacturers of gypsum products and shipped from the factories to the laboratory, where they were at once uncrated and stored at ordinary temperatures for several months before test. The assumption that they had sufficient time for drying before test is confirmed by the weights of the specimens immediately before testing.

The lime-mortar specimens, only one of which was tested, were made in the laboratory of the Lime Section of the Bureau of Standards. They were made of a consistency somewhat dryer than usual lime-mortar consistency. The mortar was tamped, like concrete, into iron molds, and left for about three days, after which the cylinders were taken out and set on end in a tray, in the laboratory, where they were saturated with water at frequent intervals during the first month and less frequently for the next several weeks, to promote setting. For three months before testing they were allowed to dry at laboratory temperatures. A sample from the interior of a duplicate of the specimen tested, taken of course from the unburned cylinder, showed the following content of water and $CO_2$, which serves as an index to the extent of setting and the extent to which the free water had been dried out: $CO_2$, 2.01 per cent; $H_2O$, driven off at 100° C, 1.90 per cent; $H_2O$, driven off at above 100° C, 7.16 per cent.

The Radix specimen was made by the manufacturers and shipped to the laboratory, where it was stored for several months at ordinary temperatures, and had attained a condition of nearly constant weight.

## VIII. THERMAL BEHAVIOR OF THE MATERIALS

The characteristic heating curves for the different classes of materials included in the investigation are shown in Figs. 4 to 10.

Specimens Nos. 1136 (Fig. 4) and 1142 (Fig. 5) represent extremes among the clay specimens, the former being made from a dense burning clay, and burned hard, whereas the latter was a light-burned specimen, made from a porous burning clay. It is consistent with theoretical considerations and with data available on the thermal conductivity of burned clays,[1] to assume that the burned clay bodies of higher porosity are of lower thermal conductivity than those of greater density. This is consistent with the relative rates of temperature rise shown on the curve sheets for these two specimens, for, as is shown in Table 1, the porosity of specimen No. 1136 was only 4.65 per cent, as against 36.7 per cent in the case of No. 1142.

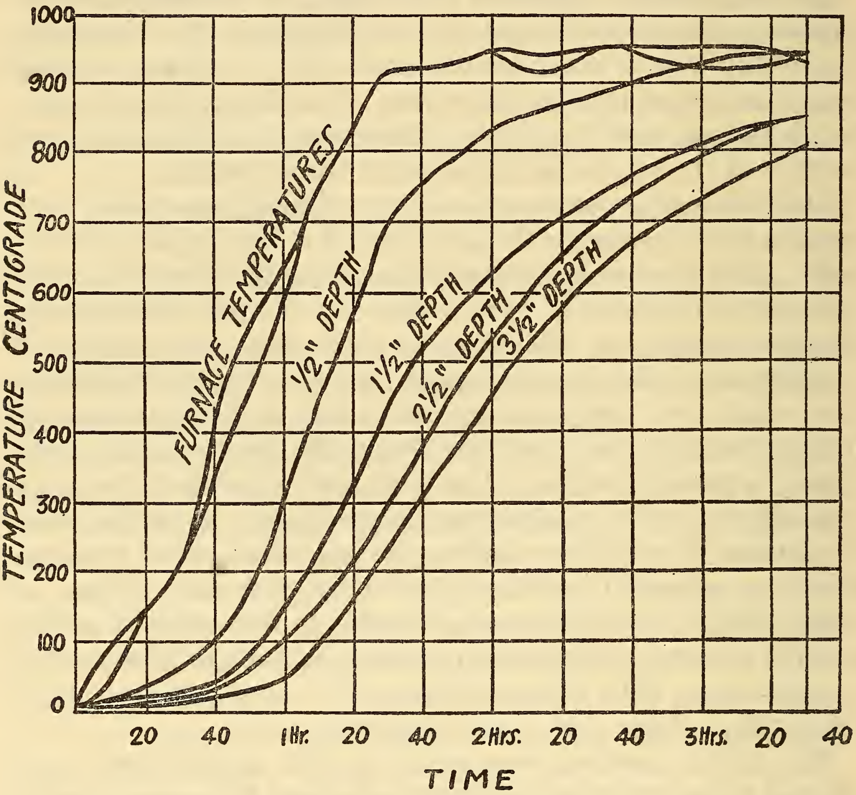


FIG. 4.—*Temperature progress in specimen 1136, a dense clay specimen*

In the curve sheets for the two concrete specimens Nos. 1211 (Fig. 6) and 1255d (Fig. 7), there is seen a pronounced lag at 100° C (212° F). This is attributable to the absorption of heat by evaporation of water. Other changes taking place in the specimen at this stage of the test undoubtedly had some influence on the temperature progress, but since it was observed that steam was given off freely by the concrete specimens in the early part of each test, and since there is such a well-defined break in the curves, particularly in those for the greater depths, at approximately 100° C, it seems reasonable to regard this as an evaporation or boiling-point lag. Whatever changes take place in the concrete in the latter part of the tests are not shown by further distinguishable breaks in the curves.

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[1] Conductivity of Refractory Materials, Dougill, Hodsman, and Cobb, Jour. Soc. Chem. Ind., 34, p. 468; 1915.

These two charts show a significant difference between the rate of temperature progress in the gravel concrete and in the limestone concrete, the limestone concrete heating up more slowly than the gravel. The same tendency is found in the data given in Table 1 and will be discussed in connection with those data.

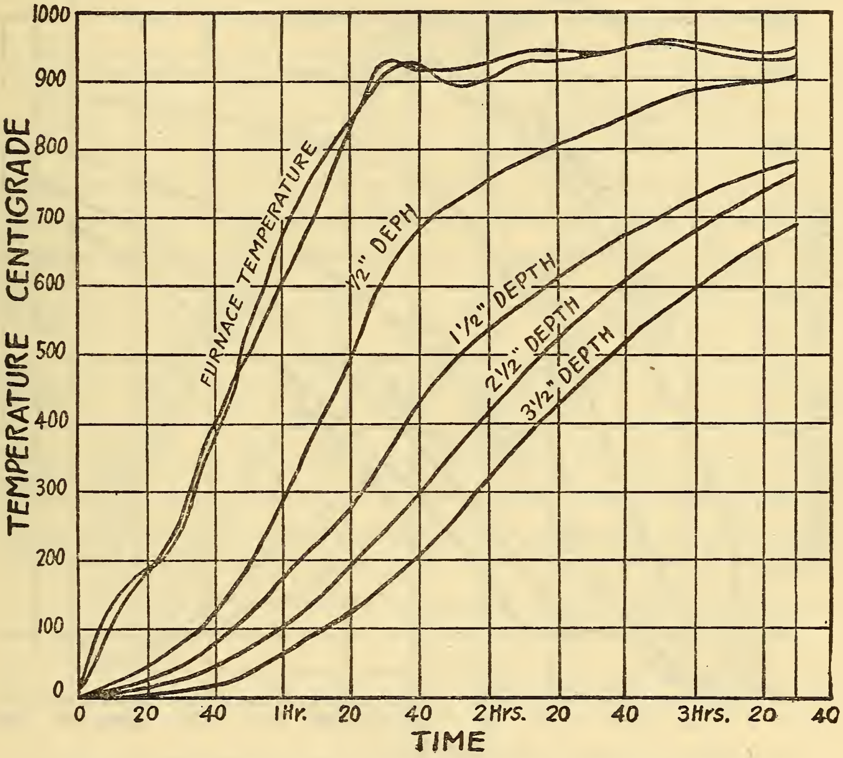

FIG. 5.—*Temperature progress in specimen 1142, a porous clay specimen*

In the curves for gypsum specimens Nos. 1443 (Fig. 8) and 1472 (Fig. 9) there is seen an important temperature lag taking place within the specimens at approximately 105° C, which is the evident effect of the dehydration of the gypsum, which is known to take place rapidly at 107° C at ordinary atmospheric pressures. The extent of this lag indicates that the heat absorbed in the process of decomposition of the gypsum is an exceedingly potent factor in retarding temperature rise through the gypsum specimens. This is strikingly shown by the contrast between these curves and those for the second burn of No. 1491 (Fig. 10). This specimen made about an average showing in its first burn. Instead of being removed from the furnace after the test, it was left in place and given a second test next day. The showing of the second test was undoubtedly influenced, in a measure, by the reduced size of the specimen, due to shrinkage, and by the cracks which were produced in the specimen in the first test, but it seems probable that most of the contrast is due to the heat absorbed by the dissociation of the gypsum, which took place almost wholly in the first burn.

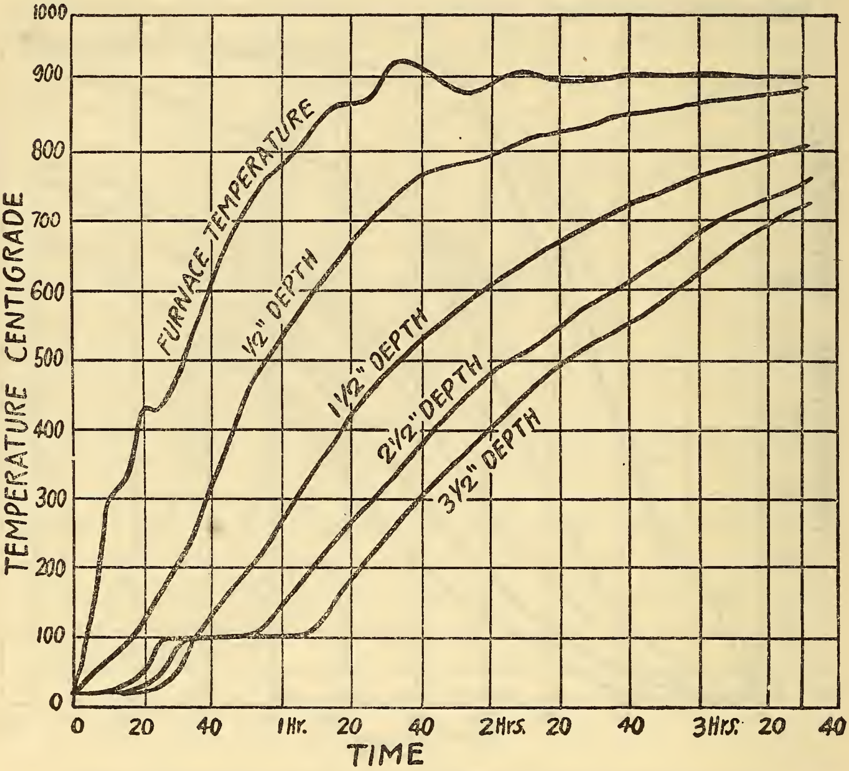

FIG. 6.—*Temperature progress in specimen 1211, a gravel concrete specimen*

Data collected from the temperature records of the tests have been tabulated as presented in Tables 1 and 2 with a view to showing, as clearly as possible:

1. The relative amounts of protection that would be afforded small steel reinforcement embedded in masses of the various materials. This is indicated by the time required for a temper-

ature of 600° C to be attained at depths of 1½ and 2½ inches. The temperature of 600° C is selected as a danger point for steel, based on the results of a preliminary investigation made by Dr. C. W. Kanolt, in the Bureau of Standards, which showed that steel tubes, tested at various temperatures, in compression, had lost approximately 50 per cent of their strength at 635° C. Perrine and Spencer[2] found that steels tested in tension lost 50 per cent of their strength at temperatures lower than 540° C.

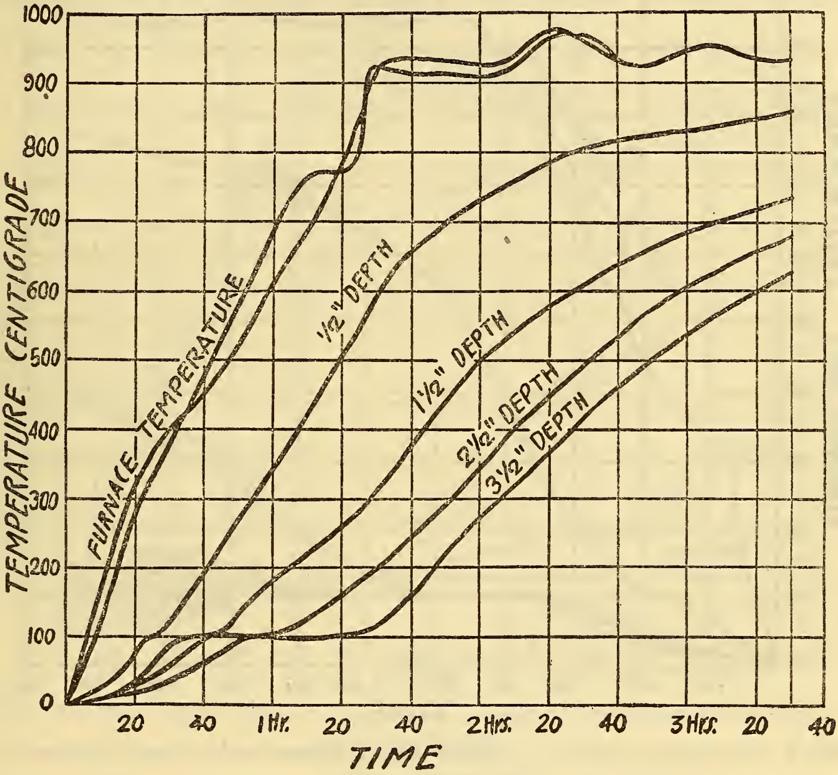

Fig. 7.—*Temperature progress in specimen 1255–D, a limestone concrete specimen*

2. The relative amounts of protection that would be afforded by these materials to larger masses of steel, such as steel columns, and the relative protections afforded the inner portion of a mass of concrete, such as a column, or a mass of gypsum, such as a floor slab, by the outer portion of the same mass. This is indicated by the temperature distribution through the specimens at the end of 3 hours and 30 minutes.

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[2] Steel and Iron at High Temperatures, School of Mines Quarterly, Columbia University, 35, p. 194.

These tables show that the length of time required for a temperature of 600° C to be attained at a depth of 1½ inches does not vary greatly in the clay and concrete specimens. The gypsums are seen to be distinctly better than the clays and concretes in this respect, only one of them reaching the temperature of 600° C at a depth of 1½ inches in the 3½-hour test. The showing of the lime mortar is similar in this particular to that of the clays and the concretes and that of the Radix is as good as that of the gypsums.

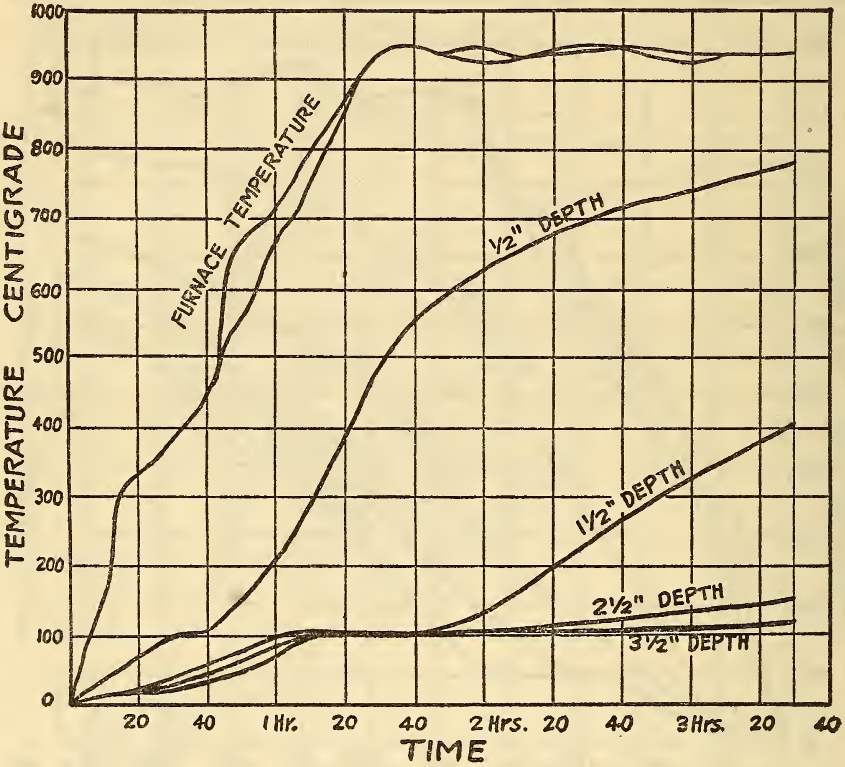

FIG. 8.—*Temperature progress in specimen 1443, a gypsum specimen from a mixture of 60 plaster, 40 water*

Contrasts are somewhat greater among the clays and concretes in respect to the time required to reach 600° C at a depth of 2½ inches. The poorest showings in this respect were made by the denser clays. Slightly more contrast would have been shown between the Perth Amboy and the Waynesburg clay specimens had the Perth Amboy specimens not been smaller than the others, on account of greater shrinkage in manufacture. The showing of the most porous clay is seen to be about on a par with that of the general run of the concretes. Among the concretes, the differences in the time required to reach 600° C at the depth of 2½ inches is not great, and some of the observable differences are attributable to higher average furnace temperatures throughout some of the burns than in others. There seems, however, to be fairly consistent evidence against the gravel concretes and those from the soft-coal cinders in this respect. In the case of the cinders the poor showing is largely attributable to the fact that some of the specimens were of very rough, open structure, and all specimens contained a large content of combustible material.

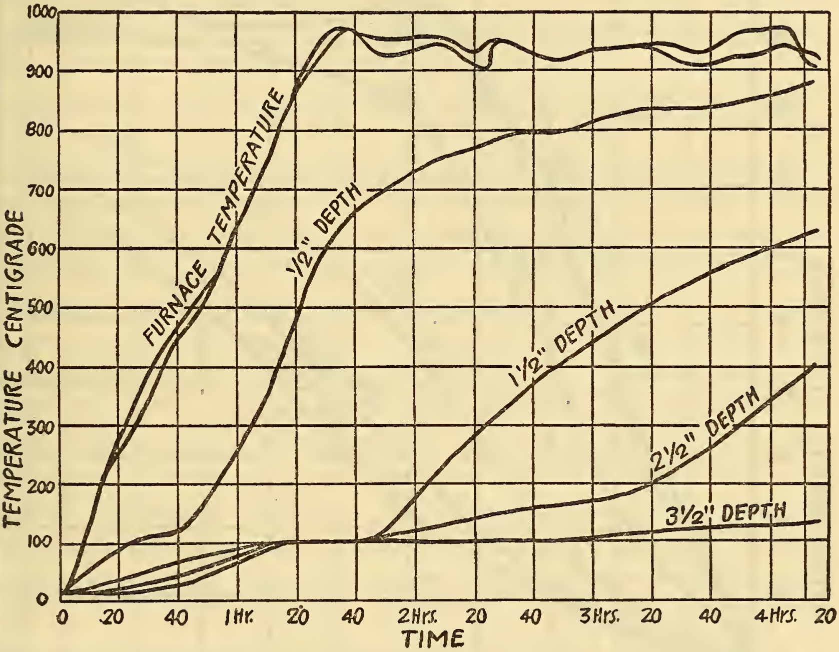

Fig. 9.—*Temperature progress in specimen 1472, a gypsum specimen from a mixture of 40 plaster, 60 water*

None of the gypsum specimens reached the 600° C mark at the 2½-inch depth. This does not apply to the gypsum specimens that were burned a second time, and which should not properly be considered in this comparison. The lime-mortar specimen made a better showing in this part of the comparison than the clays and concretes, but not as good as the gypsums. The Radix specimen did not reach 600° C at this depth in 3½ hours.

In application, the indications are that small steel reinforcement embedded in concrete would fare almost as well at a depth of 1½ inches in one of the concretes as in another, provided there were no spalling or breaking off. It is perhaps better not to extend the application of this part of the comparison to the clays, for the reason that steel reinforcement is not commonly embedded in clay in structural work. It is obvious that the gypsums indicate better protection for small embedded steel at a depth of 1½ inches than do the concretes, assuming again that the material stays in place. The indication of the lime mortar is that a thickness of 1½ inches of lime-mortar plaster on a reinforecd concrete structural member would afford approximately the same amount of protection as an equal thickness of concrete, if both were to stay in place. The Radix specimen makes the same showing as the gypsums in this respect, 600° C not having been reached at this depth.

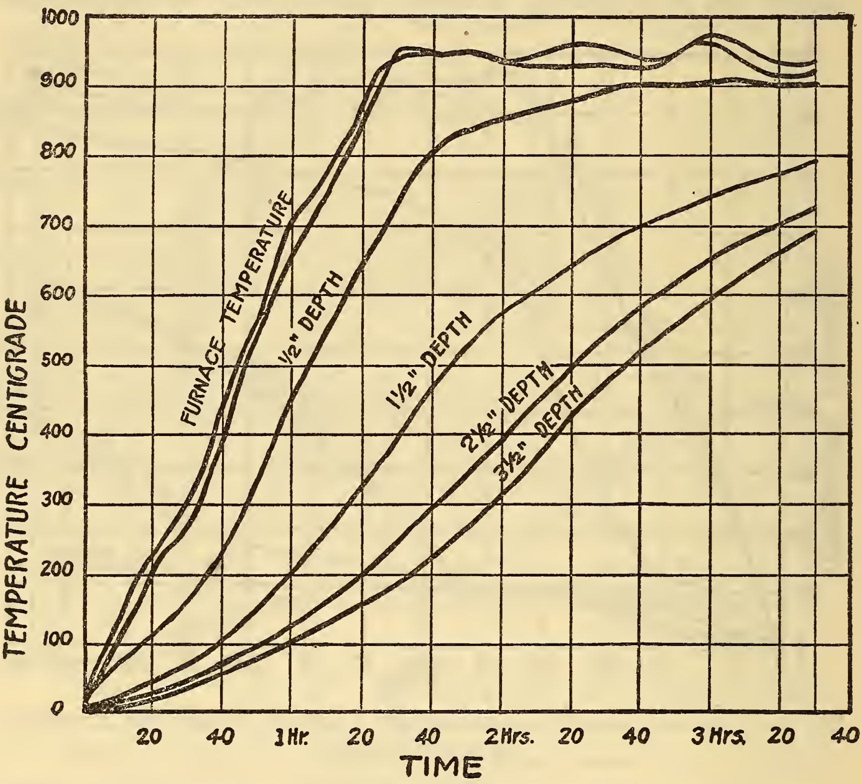

FIG. 10.—*Temperature progress in the second burn of specimen 1491, a gypsum specimen*

It is obvious that the gravel and cinder concretes afford somewhat poorer protection for steel reinforcements at a depth of 2½ inches than do the other concretes. It should be taken into consideration, however, that this does not apply to what has been termed clinker concrete, and that none of the aggregates prepared from boiler furnace refuse can properly be classed as representative cinder aggregates. In fact it is doubtful if there is such a thing as a representative soft-coal cinder aggregate.

At the 2½-inch depth the lime-mortar specimen indicated protection somewhat superior to that of the concretes as a protecting material for steel reinforcement.

Obviously, the gypsum specimens and the one of Radix, having failed to reach 600° C at a depth of 1½ inches, were far from reaching it at a depth of 2½ inches and indicate distinctly superior thermal protection for embedded steel.

Since only one of the gypsum specimens reached the 600° C point within the specified time at the 1½-inch depth, it seems desirable to make comparison among the various mixtures of gypsum included in respect to the temperatures that were reached at this depth in this time. Materials from two districts are represented and an additional variable was introduced by the use of fillers. In regard to the latter the quantity of filler did not appear to be sufficient to have an appreciable effect in the temperature rise in the specimens containing it. The two principal variables in the gypsum series were therefore the quality of the raw material and the proportions of plaster and water in the mixtures. Careful study of the data fails to discover any consistent, significant difference in the showing made by materials from different parts of the country. There is, however, a fairly consistent tendency shown in respect to the proportions of plaster and water in the mixtures. It will be noted, particularly in the last two series, where the range is greater than in the first series, that the lowest temperatures were attained at the 1½-inch depth in those specimens having the greatest proportion of plaster, namely, 60 plaster to 40 water. In other words the heavier, denser specimens did not reach as high temperatures at this depth as the lighter, more porous ones. In those proportions approximating 50 plaster to 50 water the tendency did not seem to be consistent, specimens 1481 to 1484 showing lower temperatures than the slightly denser ones 1491 to 1493. The same is seen in specimens 1451 to 1463. In the case of specimens 1471 to 1473 it is indicated that the further reduction in density results in higher temperatures than those shown by the specimens of intermediate densities in the same series, in which the range of proportions is from 60 plaster to 40 water, to 40 plaster to 60 water.

The fact that the mixtures containing the highest percentage of plaster did not attain as high final temperatures at the depth under consideration as those containing lower percentages of plaster, shows that the greater heat-absorbing capacity of the densest members of the series more than offsets the lower thermal conductivity which may be assumed in the case of the more porous ones. Those specimens which had most plaster in the mixture had most combined water to be driven off, and also had the greatest weight of material to absorb heat in the sensible form with increase of temperature. It is hardly necessary to point out the practical application of this comparison, which is, of course, that within the range of proportions of plaster and water here represented, there is nothing gained in the way of fire-resisting properties by making gypsum products porous rather than dense. The heavier, denser material, which has greater strength than that which is lighter and more porous, is the better heat insulator, according to the results of these tests. The evidence obviously is, therefore, that from the standpoint of fire protection it is bad practice to sacrifice strength for the sake of the lower thermal conductivity, which is offset by other thermal factors.

## IX. PROTECTION OF LOAD-BEARING MEMBERS

As has been suggested, some information as to the relative abilities of these various materials to protect load-bearing members, such as those of steel or concrete, may be gained from the data on the temperatures attained in the interior of the specimens, particularly at the depth of 3½ inches. The constrasts shown by the clay specimens in this respect are rather striking, the clay specimens of the highest porosity showing temperatures more than 100° C lower than those of greater density. It is seen also that specimens No. 1141 to 1143 have maintained lower temperatures at this depth than most of the concretes. These comparisons support the more or less generally accepted belief that porous clay protective coverings are better than dense ones in respect to their ability to retard heat flow, and the indications of these data are that differences in porosity are of even greater importance than is commonly supposed.

Among the concretes, those from gravel and cinder aggregates show the highest final temperatures and the limestone concretes the lowest. It should be repeated, in this connection, that those concretes here termed "cinder concretes" had a considerable content of combustible material, largely in the form of soft coke, which presumably contributed to the comparative rapidity of the temperature rise by its own combustion. The consistently lower final temperature shown by the limestone concrete specimens is rather surprising, in view of the fact that limestone concrete is not generally regarded as particularly good concrete for fire-resistive construction. In these tests the limestone concrete seems to have shown superiority over the others in point of rate of temperature penetration. If there were a consistent tendency for heat to penetrate the limestone concretes more slowly than other concretes, it would have a bearing on practical construction, since it is probably safe to assume that at temperatures higher than the ordinary, the strength of a concrete is a function of the time and temperature. This being the case, a tendency on the part of any aggregate to retard temperature rise through the mass of a load-bearing member would be distinctly in favor of its use in fire-resistive construction. Attention has already been called to the fact that in an accidental fire the thermal behavior of a material will be affected by the absorption of heat by endothermic chemical reaction, if the composition of the material be such that such a reaction will take place. In the case of the limestone-concrete specimens tested in this investigation, it was observed that on exposure to atmospheric conditions after the test, the outer portion next the cylindrical surface slaked and fell off. It was found that the thickness of the portion which came off in this way was fairly uniform and approximated $\frac{5}{16}$ inch. The slaking was, of course, due to the decarbonation of the limestone in this portion of the concrete. Calcium carbonate dissociates rapidly[3] to $CaO$ and $CO_2$ at 898° C at atmospheric pressure. It is evident therefore, that this temperature was attained in the limestone-concrete specimens to a depth of approximately $\frac{5}{16}$ inch. The temperature records of the burns of these specimens show that this temperature was not attained at a depth of ½ inch. The weight of the limestone decarbonated in each of these specimens was approximately 6 pounds. The heat of dissociation of $CaCO_3$ at 900° C as obtained by interpolation between figures given by Johnson[4] is 396 calories per g. The heat absorbed by the evaporation of water at 100° C is 540 calories per g. Therefore the quantity of heat absorbed by the dissociation of 6 pounds of $CaCO_3$ would be as great as that absorbed by the evaporation of $\frac{396 \times 6,}{540} = 4.4$ pounds of water. This is a rough approximation, as the quantity of limestone decarbonated is estimated from the approximate thickness of the layer of material that slaked off. It will suffice to show, however, that a considerale quantity of heat was taken up in this way, although it should be taken into consideration, on the other hand, that the effect of heat absorption taking place close to the surface of the cylinder would be much less than that of the absorption of the same quantity of heat taking place throughout the mass. This is obvious when it is considered that heat can reach a point near the surface much more readily than it can penetrate to interior points, so that one heat unit eliminated at a depth of about 2 inches from the surface counts for as much as several heat units absorbed near the surface.

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[3] Jour. Am. Chem., 32, p. 946.

[4] Op. cit.

Another thing which undoubtedly had some effect in the heating of the limestone concretes is that the residual CaO resulting from the decomposition of the limestone was presumably of lower thermal conductivity than the limestone itself, and this of course would result in better resistance to heat flow after the decomposition started to take place than before.

There are seen, therefore, to be two factors entering into the thermal behavior of limestone concrete which do not enter into that of the other concretes included in the series under consideration, and both of these factors have a tendency to retard the rise of temperature of the concrete mass. Taking these factors into account, there seems to be a reason for the performance of the limestone concretes in these tests. It seems reasonable to suppose also that specimens in which the average temperatures attained throughout the mass are lower than those attained in other specimens will retain more strength, other things being equal. In this investigation compressive tests were made of a number of the specimens and, as is shown in Table 1, the strength of the limestone-concrete specimens was somewhat greater than that of the other specimens which were tested for strength.

While these results are favorable as far as they go to limestone concrete as a fire-resistive material, the fact should not be overlooked that the decarbonation of limestone, to which the lower final temperatures of the limestone concrete are attributed, does not take place to any important extent in high-calcium limestones at temperatures which do not approximate 900° C, so that little thermal advantage from this dissociation would be gained in a fire unless the surface of the concrete reached such temperatures, which means that such an advantage would be gained only in fires in which comparatively high temperatures are attained.

The results obtained in this investigation differ somewhat in respect to the limestone concretes from the conclusions of Prof. Woolson from the results of his investigations in 1905 and 1906.[5] Prof. Woolson's work was done with specimens somewhat smaller than those used in this investigation, namely, 4-inch cubes and 6 by 6 by 14 inch prisms. This would tend to result in a large proportion of the limestone being decarbonated in long exposures to high temperatures and would account, at least in part, for the apparent discrepancies between the results of his 1905 tests and those shown in this series. It is to be noted that in Prof. Woolson's investigation in 1906 some results were favorable to trap rock and others favorable to limestone concrete. This would indicate that there was not enough difference between the two to show results consistently favorable to either. Considered in connection with the foregoing statements regarding decarbonation, this is what might be expected, for in Prof. Woolson's 1906 investigation the furnace temperatures did not exceed 815° C, at which there would be practically no decarbonation of a high-calcium limestone.

Among the gypsums the final temperatures at a depth of 3½ inches are only a few degrees above the dissociation temperature of 107° C, already referred to, and consequently the differences observed are small. There may be said to be a slight tendency toward a more favorable showing on the part of the heavier materials.

It is obvious that the final temperatures at the 3½-inch depth were much lower in all the gypsum specimens than in the concretes and in the clay specimens. While these results can not be expressed in the form of quantitative comparisons, they would seem to have a bearing on the relative degrees or amounts of protection afforded large protected steel or concrete load-bearing members by protective coverings of these various materials. It is true that the protection of concrete load-bearing members by gypsum coverings is not common practice, yet it may be regarded as a future possibility, and these results indicate that from the standpoint of heat insulation there is much in its favor.

The final temperature in the lime-mortar specimen was somewhat lower than that in any of the concretes, which is again favorable to lime-mortar plaster. The showing of the Radix specimen in respect to the final temperature is seen to be somewhat poorer than that of the gypsums.

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[5] Investigation of the Thermal Conductivity of Concrete and the Effect of Heat upon its Strength and Elastic Properties, by Prof. Ira H. Woolson, A. S. T. M., 5, 1905; and 6, 1906.

## X. CONDITION OF SPECIMENS AFTER TEST

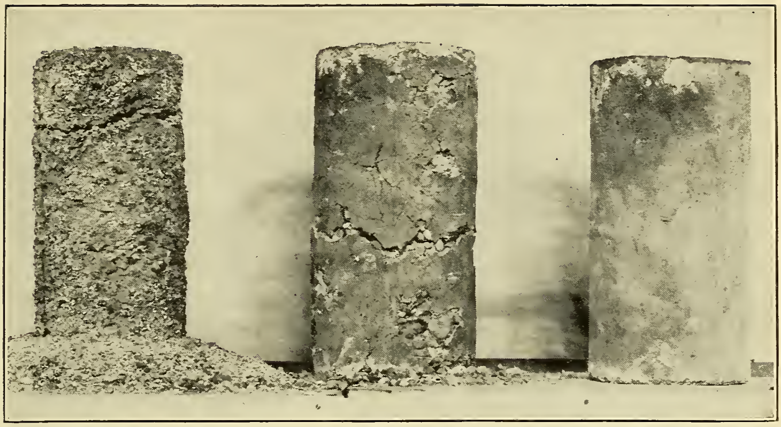
All specimens were examined after test with a view to obtaining information as to the extent of injury suffered by each kind of material. There was no satisfactory comparison possible among the clay specimens, because of the fact that all the clay specimens were cracked to some extent in the burning before being submitted to test. It may be said, however, that there was no spalling in this series of tests on the part of either the clay specimens or those of any of the other materials.

In the concrete series certain tendencies were apparent. All the gravel-concrete specimens were very weak after test and many of them were found to be broken in two, about midway between the ends, when taken out of the furnace. All of them were so weak and so easily disintegrated as to be easily broken up with the hands. The 1:3:6 mixture was somewhat weaker than the 1:2:4 material, and those specimens in which 15 per cent of the cement had been replaced by lime hydrate were even weaker than the others. None of the gravel-concrete specimens would bear handling well enough to make it seem worth while to try to get them into the testing machine intact, which accounts for the fact that no results of strength tests are shown for this part of the series.

While concretes from the other aggregates were also weak after test, the gravel concretes were the poorest of all in this respect. Attention is given to the probable causes of this tendency further on in the report, following the description of the condition of the other specimens after test.

The clinker-concrete specimens all remained intact through the test and several of them were used over and over as end cylinders in succeeding tests, being burned several times without breaking or showing marked evidence of distress, although the sharp edges became worn by successive handlings. When broken for further inspection, these cylinders offered a fair amount of resistance to blows and to manual efforts to disintegrate them.

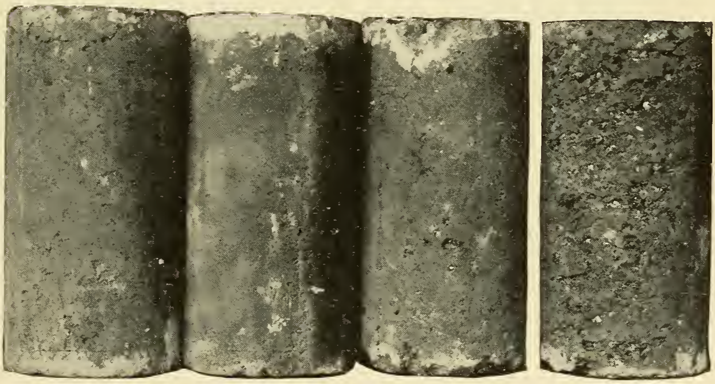
Most of the limestone-concrete specimens were intact when removed from the furnace, but a few of them were broken in two laterally, near the middle. Except for the thin outer layer previously referred to, which slaked and fell off, the limestone-concrete cylinders were stronger and more nearly sound than those from other kinds of concrete with the possible exception of the clinker concretes. This does not apply to specimens No. 1254a



(*a*) (*b*) (*c*)

FIG. 11.—*Characteristic appearance of burned specimens*

(*a*) Specimen No. 1262, limestone concrete; (*b*) specimen No. 1214, gravel concrete; (*c*) specimen No. 1233-a, clinker concrete



(*a*) (*b*) (*c*) (*d*)

FIG. 12.—*Other concrete specimens after burning*

(*a*) Specimen No. 1313, trap-rock concrete; (*b*) specimen No. 1332, slag concrete; (*c*) specimen No. 1363, cinder concrete, 1:3:6; (*d*) specimen No. 1383, cinder concrete, 1:0:6

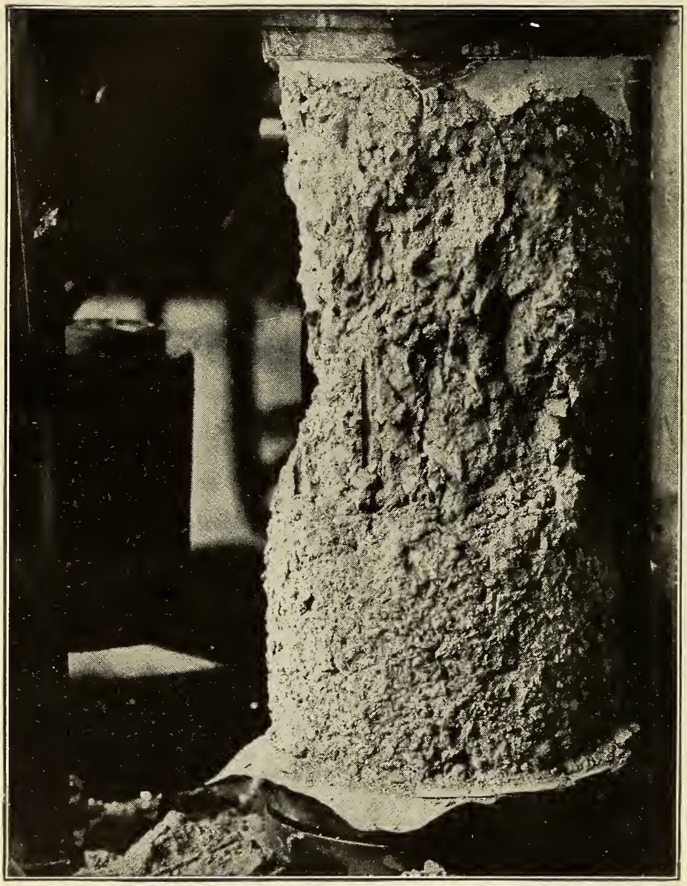


FIG. 13.—*Limestone-concrete specimen after compression test*

to No. 1254d, which had been stored in a damp atmosphere and were comparatively green when tested. Two of these specimens were weak and showed extensive splits. There was a pronounced tendency in these two specimens for the outer inch of the concrete to come loose from the inner portion. The third of these specimens did not show any marked difference, on ordinary examination, from the other limestone-concrete specimens.

Cinder concretes Nos. 1291 and 1292 were extremely weak and friable. The appearance of the concrete indicated too great a proportion of fine material, and this probably contributed to the weakness of these specimens, as the cinders that had been passed over a ½-inch screen to get the ashes out were afterwards broken down to reduce the large lumps, producing a considerable proportion of fine material which was left in.

Cinder concrete No. 1291a was an extremely rough specimen, because of a deficiency of fine material, as there was no sand in the mixture, but the interior seemed sound and fairly strong. Such a mixture is not to be recommended for further investigation, however, as this specimen made a particularly bad showing in respect to temperatures attained at all depths.

The trap-rock specimens were not easily handled without breaking after test. They were tender and easily disintegrated by slight shocks or blows. It should be taken into consideration in this connection that the trap-rock aggregate was rather coarse and not well graded.

The specimens of blast-furnace slag concretes held together fairly well after test, but were easily disintegrated by a slight shock or blow.

The appearance of several of the concrete specimens several weeks after test is shown in Figs. 11 and 12. No. 1262 was broken in handling. Fig. 13 shows No. 1256a in the testing machine after breaking, which was done several weeks after the heat test.

On account of the number of variables in the gypsum series, it is difficult to discover tendencies on the part of gypsums from one locality to retain more strength than those from another. For the same reason the effect of filler on the strength, after test, was difficult to determine. It seemed, however, that other things being equal, the more porous members of a series were weaker after test than the denser members of the same series. The Nova Scotia gypsums, none of which had any filler, were weaker in general after test than specimens having the same proportions of plaster and water among the gypsums from the Middle West, which contained filler. All of the gypsum specimens were weak after the test, which is a condition to be expected in view of the fact that the test was of sufficient severity and duration to nearly, if not wholly, complete the dehydration of all the gypsum in each specimen.

In all of the gypsum specimens there was considerable shrinkage and a characteristic cracking or checking of the surface material, which was similar to the cracking of mud that has dried in the sun and is shown in Fig. 14. Deep cracks, such as the two seen in this photograph, were found in some of the specimens and not in others. All of the specimens in the series from No. 1441 to No. 1473, inclusive, showed the peculiar structure shown in Fig. 16.

Fig. 15 shows the characteristic appearance of the specimens which had asbestos filler and those which had cut excelsior filler. The fairly well defined rings of different shades show the progress of oxidation through the mass of the cylinders. Specimen *A*, shown in Fig. 15, had asbestos filler. In all of the specimens with asbestos filler, the asbestos within approximately 1 inch of the cylindrical surface was of reddish color, crisp, and without strength. Deeper than 1 inch it was soft and flexible, light colored, and apparently unaltered. In those specimens containing wood, oxidation appeared to be complete to a depth of from 1 to 2 inches, and the material was partially oxidized to a further depth of ½ to ¾ of an inch. The remainder of the interior of the specimens was dark colored and the wood more or less charred. In some specimens there was so little of the filler that its presence was shown mainly by small, isolated, discolored patches, in the central portion of the specimen.

## XI. FACTORS WHICH PROBABLY CONTRIBUTED TO THE EXTREME WEAKNESS OF GRAVEL CONCRETE SPECIMENS AFTER TEST

The effect of heat on the strength of a concrete may be regarded as the result of changes in the strength and elastic properties of the cement itself, combined with the effect of stresses produced by the expansion of the various masses of materials of different kinds of which the concrete is composed. There is much evidence that Portland cement loses strength at high temperatures and some work has been done with a view to determining the loss in strength at various temperatures. According to the results of work done by J. E. Howard at the Watertown Arsenal in 1902, 4-inch cubes of neat cement, heated gradually to various recorded

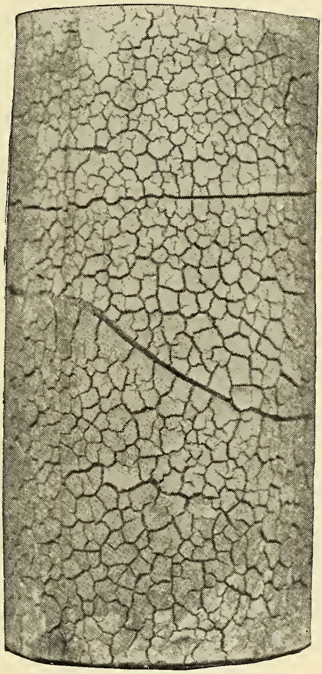


FIG. 14.—*Gypsum specimen after burning*

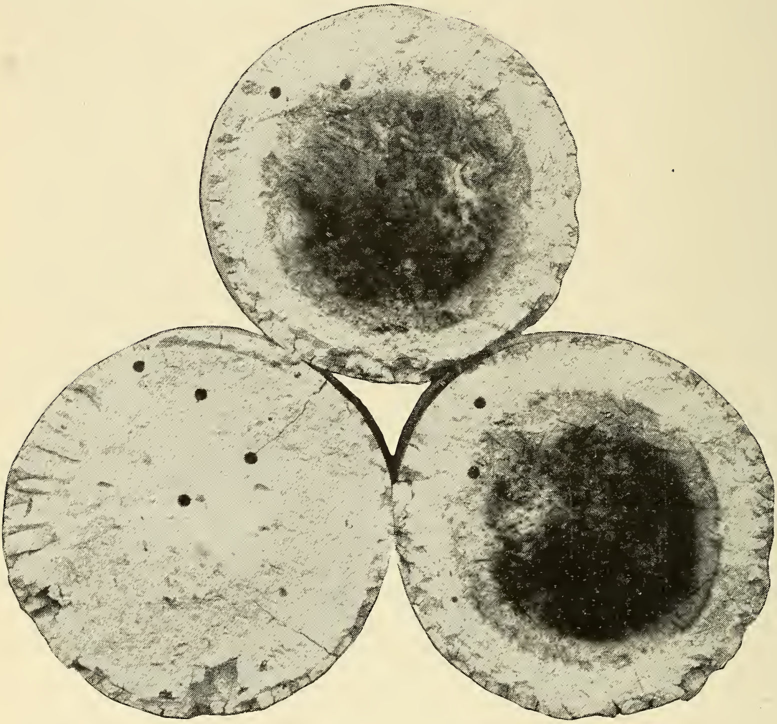


FIG. 15.—*Gypsum specimens after burning*

(*a*) With asbestos filler; (*b*) with cut excelsior filler; (*c*) with cut excelsior filler.

temperatures, cooled and tested, did not undergo much change in strength after heating up to 300° C. The strength diminished somewhat after heating to between 300° C and 425° C and diminished more rapidly after heating to between 425° C and 480° C.

Results of any work on the determination of the loss of strength of cement at different temperatures is necessarily unsatisfactory unless done in a most thorough and exhaustive way. It is next to impossible to secure uniform temperature distribution at high temperatures in a specimen of as low thermal conductivity as cement, and any approximation to uniform high-temperature distribution secured by means now in use must necessarily require considerable time for its accomplishment. It is conceivable and even probable that cement may continue to lose strength if held at any stationary temperature above some minimum not yet established. It seems probable, therefore, that the strength of a cement specimen would not be dependent solely upon the temperature to which it had been heated, but would be the resultant of a number of factors, including the length of time required in bringing it up to a given temperature, the length of time it was kept at that temperature, and the conditions of cooling, all of these having a possible bearing, not only on the inherent strength of the material, but on the internal stresses introduced. So far as the present investigation is concerned, it seems probable that the direct effect of heat on the strength of the cement in the concrete specimens would be greatest in those specimens in which the highest temperatures were attained. On this basis alone the gravel-concrete specimens should be among the weakest, but not necessarily weaker than some of the others.

The further explanation suggests itself that the shape and smoothness of the pebbles in the gravel concrete might contribute to its final weakness. While it is conceivable that this would be true in cases where the strength of the cement had been almost wholly destroyed, it does not seem probable that the roundness and smoothness of the pebbles can be accountable for any great part of the contrasts observed in the final strength of these specimens.

## XII. IMPORTANCE OF EXPANSION

The appearance of these specimens, after test, taken in connection with test observations on larger specimens, would indicate that a very important factor in the effect of heat on concrete is that of expansion. The expansion at high temperatures is one of the properties of concretes which have not been thoroughly investigated. It is known, however, that the expansivity of concrete depends in part on the richness of the mix and the moisture content and that it varies with the temperature. Inasmuch as the coarse aggregate constitutes a large portion of the mass, and since the expansion behaviors of the various materials commonly used for coarse aggregate are known to differ greatly from each other, it seems reasonable to look to the aggregate for a large part of the expansion differences in concretes, and consequently for a large part of the differences in the behavior of different concretes when subjected to fire. Data are available on the expansion of three natural rocks which enter to a very important extent into concrete aggregates,[6] and a comparison of the behavior of these three may throw some light on the expansion, and consequent performance of different concretes at high temperatures. (See Figs. 17 and 18.)

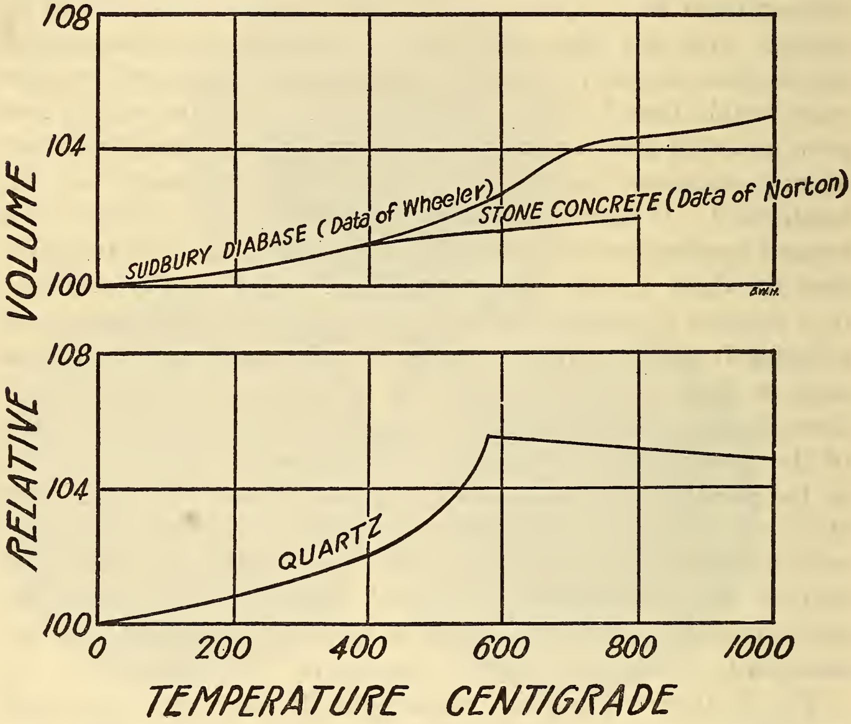


Fig. 17.—*Temperature-volume relations*

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[6] The Determination of Mineral and Rock Densities at High Temperatures, by Day, Sosman, and Hostetter, Am. Jour. Sci., 37, p. 1; 1914.

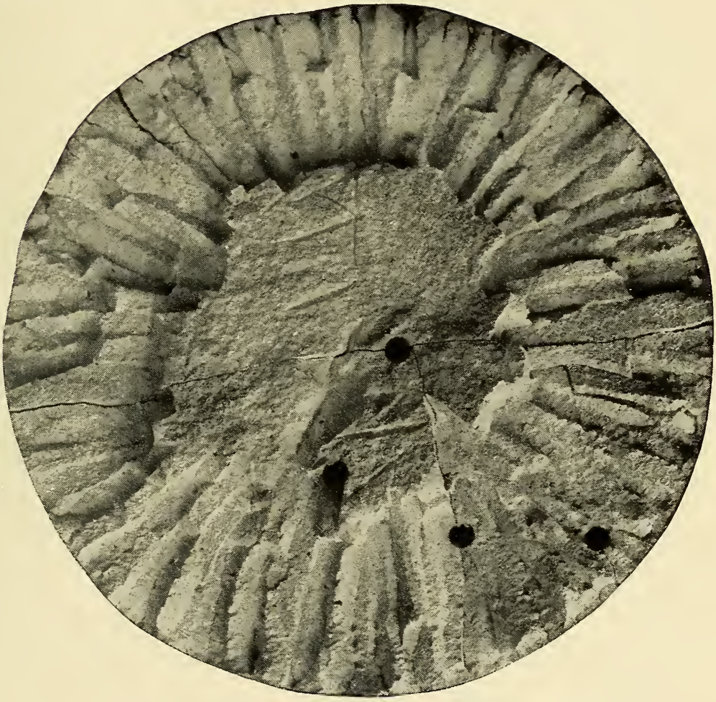

FIG. 16.—*Gypsum specimen after burning; no filler*

In the curve for quartz, Fig. 17, it is shown that the rate of volume increase with rise of temperature increases with the temperature, up to 575° C, and that the rate increases very rapidly in the last 100 degrees preceding the inversion point, 575° C, at which there is a discontinuity in the direction of the curve- Beyond the inversion point there is apparently a slight contraction up to about 950° C. Beyond that temperature it is reported that escape of gases made accurate measurements impossible up to 1250° C.

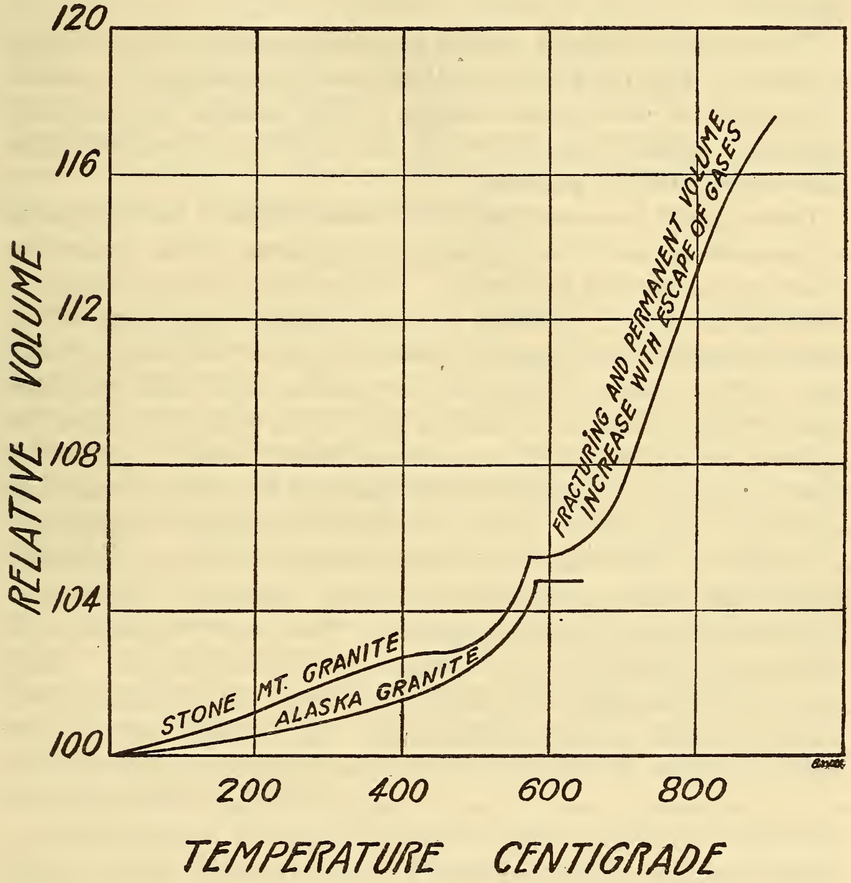

FIG. 18.—*Temperature-volume relations*

The quartz specimens were from Minas Geraes, Brazil, and were in the form of clean, transparent blocks. It is reported in this connection that there was very little cracking in the specimens. The volume changes were reversible and the data obtained on cooling were practically the same as those found with rising temperatures.

Two granites are compared in Fig. 18, one of which is described as a "pink, coarse-grained, quartzose granite from Kasaan Peninsula, Alaska," and the other as a "gray, biotite-muscovite granite from Stone Mountain, Georgia." In connection with these curves, the author of the work says: "Above 575° C granite undergoes a permanent dilation caused by the shattering effect due to the different expansion coefficients of its minerals and to the escape of gases."

The curve for Sudbury diabase is given because of the similarity of this rock with the Palisade diabase, commonly called trap rock. It is seen that the volume changes in this material are not only somewhat smaller, but that they are much more gradual than those of quartz and granites.

There should be some sort of correlation between the expansion of the diabase and that of the stone concrete whose expansion behavior was studied by Norton.[7] The concrete used in Norton's investigation was 1:2:5 stone concrete, and the expansivity of the coarse aggregate was probably similar to that of the Sudbury diabase, yet the volume changes in the concrete were much less than those of the diabase, as is seen in Fig. 17, in which the curve for concrete was obtained by calculation from Norton's figures for linear expansion. Attention should perhaps be called, in this connection, to the question of the correctness of the term "expansion" as applied to the length or volume changes of these materials. Norton uses the term "coefficient of linear expansion," which conveys the idea of a physical constant. This use of the term does not seem justifiable in view of the nature of the material. Concrete is not a homogeneous material, nor are all the substances composing it stable at high temperatures. Its volume changes with temperature are the resultants of various unequal volume changes of its components, part of these changes probably being negative and due to chemical changes, whereas others are more or less permanent volume increases caused by the shattering action taking place in the natural-rock fragments of the coarse aggregate. It is conceivable that such a shattering action, due to the unequal expansion of the component materials, and also to the evolution of steam and other gases, may take place in the concrete mass as a whole, and that this may be accountable in part for the permanent elongation which Norton reports to be, at 1500° F (815° C), 75 per cent of the total elongation. In view of these considerations, it would seem better to refer to the results of such measurements as these as changes of length with temperature, rather than as coefficient of linear expansion. However, these measurements do give the resultants which by calculation become comparable with the volume changes with temperature, given for the natural rocks, quartz, granite, and diabase. It is rather surprising to note how much less the volume changes are in the concrete than in any of the natural rocks, even the one which is similar to the coarse aggregate which was the predominant component of the concrete investigated. This suggests the possibility of restraint and of internal stresses which might become destructive, especially with quick heating and most especially in the case of an eggregate like either quartz or granite, in which excessively rapid volume changes take place within a definite temperature region.

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[7] Some Thermal Properties of Concrete, by Chas. L. Norton, Jour. Am. Soc. Mech. Engs., June, 1913, p. 1011.

## XIII. SUMMARY

In summing up the results of this investigation, it is important to bear in mind that the investigation was of a preliminary rather than of a final nature, and that while it shows, fairly clearly, certain tendencies in the thermal behavior of the materials which have a bearing on their insulating, and to some extent on their load-bearing properties, final conclusions as to the value of any material for use in fire-resistive construction should not be drawn from this work alone. All of the classes of material represented in this work have certain strong and certain weak features. All of them have their proper places in fire-resistive construction, and the chief value of the experimental study of their properties is to supply information that may tend to promote their more consistent, economical, and effective use, which would in turn tend to promote their more extensive use by making fire-resistive construction a better financial proposition.

It is necessary, also, to differentiate between fundamental tendencies in the materials themselves and the relative efficiencies of the structural units or devices that can be made from them. For example, temperature progress is seen to be comparatively rapid in some of the clay specimens, but no attempt is made to deduce from these results comparisons between hollow tiles or blocks made from these clays and solid masses of burned clays or of any of the other materials under consideration. The scope of the investigation is not such as to make such an attempt advisable.

Perhaps the most significant indication shown by the clay specimens is the wide difference in the rates at which temperature progress took place in the different clay cylinders. There is strong evidence here of the superior insulating value of the porous burned clay over that which is denser. Since it is largely a matter of thermal conductivity, in the case of the clays, and since the showing is entirely consistent with the existing data as to the thermal conductivity of burned clays, it seems reasonable to expect that porous-clay wares will give better thermal protection, other things being equal, than denser ones, and it would seem advisable that more general recognition be given to this quality in specifications for fire-protective coverings of burned clay. Special experimental work on the relative efficiencies of such coverings, comparing the denser with the more porous coverings, would be necessary in order to determine how far such specifications should be carried. It seems reasonable to predict, however, that such an investigation, by bringing out quantitatively the effect of different degrees of porosity on the efficiency of the actual coverings built up from actual structural units, hollow or solid, protecting actual steel members, would bring out information which would eventually make such protection more reliable and more economical than it usually is now, when no definite specifications as to porosity are in effect.

In the concretes the principal variable is the aggregate, and but little difference is indicated as to the ability of concretes of various aggregates to protect reinforcing steel placed near the surface. Greater differences are shown as to the final temperatures attained near the center of the specimens and in the strength left in the mass of the concrete after the test. These indications are somewhat favorable to slag concrete and particularly so to limestone concrete. The showing of gravel concrete, on the other hand, is somewhat unfavorable in respect to temperatures attained in the interior, and distinctly so in respect to the strength of the concrete after test.

In regard to the slag and limestone concretes, the results of this very limited work should not be taken as conclusive evidence of the superiority of concretes from these aggregates. In the case of limestone, it has been shown that under the conditions of these tests a chemical reaction took place which would tend to keep the internal temperatures down to some extent; but it has been pointed out, also, that such a reaction would not take place except above a certain temperature limit. It may be added that the temperature limit would be different with different limestones. On the other hand, the evidence here presented is contrary to the more or less general belief that crushed limestone is an inferior aggregate for fire-resistive concrete.

In the case of the gravel, however, the situation is different. Besides attaining rather high final temperatures in the interior, the gravel concretes were all extremely weak after test, and this observation is in keeping with that of Prof. Woolson in his investigations, previously referred to. It is also in keeping with observations reported to him by the British Fire Prevention Committee and with observations as to the behavior of gravel concretes in accidental fires in different localities in this country. Furthermore, our information as to the thermal conductivity, and particularly as to the expansion of quartz and of materials composed largely of quartz, is unfavorable to gravel as an aggregate for fire-resistive concrete. Other investigations now under way will be productive of evidence along this line, and it seems of considerable importance that as much work as is necessary to demonstrate conclusively the suitability or unsuitability of gravel for fire-resistive concrete should be done without delay or interruption.

The evidence as to the effect of lime hydrate on the strength of gravel concrete after exposure to fire, while unfavorable to the hydrate, is based on the results of entirely too few tests which cover too narrow a scope to be conclusive.

Gypsum specimens all showed relatively slow temperature progress and also low strength after test. The time-temperature charts speak for themselves as to the importance of the heat absorption, by the chemical dissociation of the gypsum, in the protective efficiency of this material. While no great contrasts were found in the behavior of the different gypsum mixtures included in this work, there was fairly consistent evidence that the heaviest, densest mixtures were better heat retardants than the lightest, most porous ones, indicating that the greater thermal capacity and greater heat absorption by dissociation, in the densest specimens, outweighed the lower thermal conductivity which may be assumed for the most porous ones.

Lime mortar showed a heat-retarding ability which tends to promote respect for this material in fire-resistive construction, and the material called Radix made a showing which indicates that new combinations of materials may be expected to enter the field of fire-resistive construction.

In the general scheme of conservation of resources and of the safeguarding of human life, a much more complete knowledge of the properties and of the most suitable application of the available materials of construction is needed. The theoretical study of heat flow as applied to these materials of construction, under fire conditions, would necessarily be so complex as to render such study, by itself, exceedingly inefficient. Experimental methods are obviously essential to satisfactory progress in securing vital information along this line and it is equally important that final judgment on various points should be reserved until enough evidence is available to justify such judgment.

WASHINGTON, July 2, 1918.

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